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Formation of Back-Spattered Bloodstain Patterns: Air Flow Visualisation and Form of the Damage in a Brain Tissue Simulant

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Abstract

Back-spattered bloodstain patterns are often important in investigations of cranial gunshot fatalities, particularly where there is doubt whether the death is suicide or homicide. Back-spatter is the projection of blood and tissue back toward the firearm. Three mechanisms are known to cause back-spatter: the interaction of blood with muzzle gases; a momentum effect known as tail-splash, and the collapse of a temporary cavity which forms around the wound channel [1]. The simulant most widely used at present for human soft tissue is gelatine gel, with 10 and 20 % w/w concentrations of gelatine [2-4]. Recent work has questioned the validity of the use of this material as a brain simulant [5]. Two series of experiments were performed to understand the effect the elastic response of different materials has on the form of the permanent damage and the ejection of air from the temporary cavity. The results indicate that by reducing the elasticity of the material the cross-sectional area of the permanent wound track increases. None of the simulants used in this experiment experienced exactly the same form of damage as bovine brain. Air ejection observed in the gelatine gel was caused by air being drawn into the temporary cavity at the moment of formation with an average velocity of 64.8 m/s, 75.6 m/s and 81 m/s for 10%, 5% and 3% gelatine respectively. The average velocity of the air ejected from the entry hole was 72 m/s for 10% gelatine, 43 m/s for 5 % gelatine. By reducing the elasticity of the material, the velocity of the ejected air reduced. Air ejection was not observed from bovine brain, nor from simulant material M1 [5]. Overall, this study suggested that the ejection of the blood from the head is strongly dependent on the pressure inside the skull. It is hypothesised that the elasticity of the brain is not enough to cause the ejection of the blood backward. However as the bullet penetrates the head, pressure inside the head increases and this pressure has the potential to eject the brain and blood backward towards the firearm.

Introduction

In the last two decades, the number of incidents resulting in gunshot wounds have increased [6]. One of the important factors to ascertain the scenario of the incident is bloodstain pattern and backspatter, the projection of blood from the entry wound back towards the weapon [1, 7].Therefore, it is important to understand the mechanism of formation of the backspatter, and particularly in cranial wounds where it is pronounced. There are several theories about formation of the backspatter such as kinetic energy dissipation, collapse of the temporary cavity and elastic response of the material [1]. Ballistic gelatine is commonly used as a simulant for soft tissues as it has the same bullet stopping distance and similar density to porcine muscle [8-10].In studies by Zhang et al [4], Sylgard527 and gelatine have been used as brain simulants to measure the pressure distribution created by the bullet. However, there is a lack of validation of the gelatine as a brain simulant in the literature. Brain is a viscoelastic material consisting of different tissues such as white matter, grey matter and blood vessels. This makes it challenging to find valid data for the high strain rates, which occur in gunshot wounding. In this paper, two series of experiments were performed to illustrate differences between bovine brain and different materials used as simulants for human soft tissues. The first set of experiments focus on to the form of deformation in different materials shot with an air rifle and the second set concentrates on visualisation of airflow in front near the entry wound caused by a 9 mm FMJ bullet.

Experimental setup (form of the permanent damage)

The stopping distance of the impact of a 1±0.006 gram, round nose diabolo projectile from a .22 calibre air rifle, which had a velocity of 290±2 m/s was compared between bovine brain, 10%, 5%w/w Glita bovine gelatine (bloom 240-260) and a new material (M1) as a brain simulant. The test samples were 95x95x430 mm^3. The method of the preparation of gelatine and M1 can be found in previous work [4]. The experimental setup is shown in Figure 1.The distance between the muzzle and the samples was 410 mm.

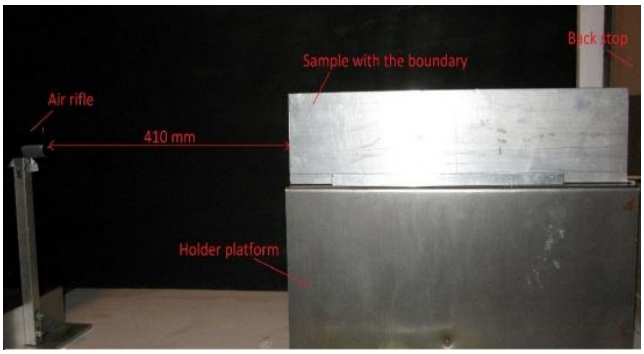

Figure 1. Experimental setup

The brain samples were made of 6 to 7 individual brains as they have different size. Brains were placed side by side giving a path length of 430 mm in the bullet direction. All samples were shot with two different boundary conditions. The first was a constrained boundary with a 3 mm aluminium plate on all surfaces excluding the bullet entry and exit surface. The second was unconstrained apart from the ground plane.

Experimental Setup (Flow Visualization in Front of the Wound Cavity)

The set-up for high speed imaging is shown in Figure 2. The experiments were recorded using Photron SA1.1 (resolution 384×432 pixels) and Photron SA5 (resolution 640×376 pixels) cameras (key parameters are shown in Table 1. The samples were shot with 7.45g 9 mm full metal jacket bullets (American Eagle). A Glock model 17 hand gun clamped to a firing bench was used

in this experiment. Bullet velocity was calculated by tracking the bullet displacement between individual images. Uncertainty in velocity due to the pixilation of the bullet and consequent uncertainty in position of the projectile produced a maximum uncertainty in velocity of ± 5%. The initial velocity when the bullet enters the image frame is 350 m/s. Four LED lights were used for the front lighting and two Kaiser Halogen video lamps were used for backlighting.

Camera	Frame rate	Shutter speed	Type of lens	Light
SA1	30000	1/220000 s	90 mm Tamron	4LED(32000 lm) Kaiservideo lamps (2000 W)
SA5	30000	1/220000 s	50 mm Nikkor	

Table 1. Camera and illumination parameters

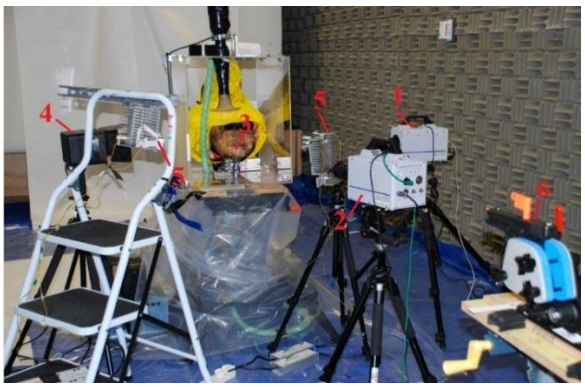

Figure 2. Experimental set up; 1- SA5 2- SA1 3- Sample holder 4- Kaiser Video lamp 5- LED lights 6- Gun

In order to visualise the air motion in front of the wound cavity a sheet of smoke was arranged perpendicular to the path of the bullet. In order to generate a laminar flow of smoke with a constant velocity a Rave model 1214 smoke generator was connected to a reservoir box with a heat resistant tube. A 1.5 W computer cooling fan was installed at the output of the reservoir to accelerate the smoke with a velocity of 1 m/s along the pipe to the open section. A suction nozzle was installed 200 mm from the tip of the pipe to create a narrow jet of smoke in front of the entry wound. To return the smoke back to the reservoir a 2 W fan was installed at the end of the nozzle. The experiment was performed on blocks of 3, 5 and 10% w/w gelatine as well as bovine and sheep heads. The animal heads were collected from Auckland Meat Processors Company. Animals were electronically stunned before their neck arteries were severed with a knife. The heads were removed from the body 10 to 15 minutes after death. The heads were shaved on the frontal section where bullet impact would occur. All the samples were kept at room temperature (18-22 ºC). The distance between the entry hole and smoke line varied (10 to 25 mm) in each set of experiments due to the difference in anatomy of the animal heads. The distance from the gun to the samples was 1m. To prevent the forward-travelling muzzle gases from affecting the air motion near the sample, a sheet of sandwich-wrap plastic was installed between the gun and samples.

Results

Figure 3 shows the stopping distance of the projectile in 5 and 10% gelatine and bovine brain without the boundary. The stopping distance increased as the percentage of the gelatine decreased from 269 ±10 mm at 10% w/w to 402±10 mm at 5% w/w. The primary difference between these two gels is the elastic modulus. The projectile stopped at a depth of 390 ±10 mm in the bovine brain sample. Measurements were taken by visual inspection of the permanent wound track in the transparent materials and by cutting the brain samples into 10 mm slices (as its opaque nature made visual inspection impossible). Errors of up to 10 mm may occur during the cutting of the brain samples, hence the uncertainty. Error bars in Figure 3 are ±10 mm, higher than standard deviation from three repeats for each material.

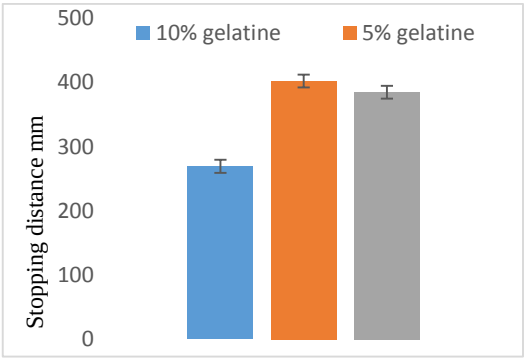

Figure 3. Stopping distance of the projectile in different materials

The effect of the boundary condition on the depth of penetration was compared in different materials. For 10 % gelatine, with a rigid boundary, depth of penetration is less by about 14 mm, compared to unconfined samples. However, there was no significant difference with 5 % gelatine. The experiment with the rigid boundary on bovine brain was not successful as containing the bovine brain in the aluminium block is difficult. One brain is not big enough to fill the block. Therefore, it is necessary to use several bovine brains on top of each other, as brain is not homogeneous, it is difficult to fit the boundary around the sample.

For wound track damage analysis, all the samples were cut into slices with 10 mm thickness. In order to have a constant thickness of the material, a cutting template was used. Each block of the material was placed into the template and was cut with a kitchen knife. An image of each slice was taken using a Nikon D600 camera with a 130 mm macro lens. Two LED lights with 10000 lm were used for illumination. Each sample was sprayed with flawfinder penetrate spray (ROCOL) to visualize the cracks in the samples. The crack detection liquid was cleaned from the surface so the remaining paint in the crack gave good contrast for visualization of the permanent damage. Figure 4shows an example of the form of damage on the wound channel in 10% without boundary condition (left photo) and gelatine with rigid boundary (right photo) and. The damage takes the form of a large crack in one side in the 10 % gelatine samples with the rigid boundary. This large crack rotates clockwise through the 10 mm slice samples, which is the direction of the rotation of the bullet due to the barrel rifling.

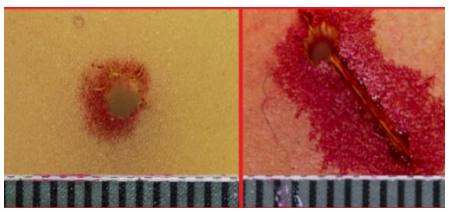

Figure 4. Form of the damage in 10% gelatine with the rigid boundary at right and without boundary at left

One large crack at one side of the bullet path was observed in the 5% gelatine experiment with the rigid boundary. In 5% gelatine three large cracks can be seen through all wound tracks in the samples without boundary. The rotation of the wound cavity was observed in 5% gelatine samples.

Figure 5 shows the form of the permanent wound channel from the first slice in all three materials. The scale in each image has1 mm divisions. Neither of the gelatine mixtures mimicked the form of the damage of the bovine brain. The central hole in the gelatine

samples has a circular shape, and in the bovine samples, it is more elliptical.

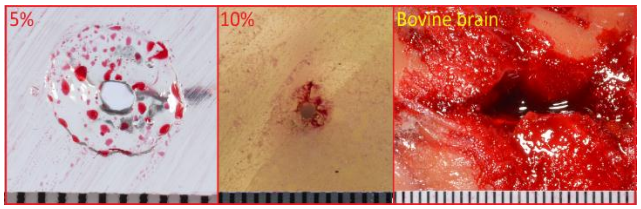

Figure 5. Form of the permanent cavity at the surface of the bovine brain 10% and 5% gelatine. Red areas are Rocolflaw finder

Figure 6 shows an example of the measurement of area of the permanent cavity in 10, 5 % gelatine and bovine brain. Each image was calibrated separately to reduce the errors in image processing. Measurements were taken using ImageJ [11] by fitting a polygon in the centre of the wound track (yellow line).

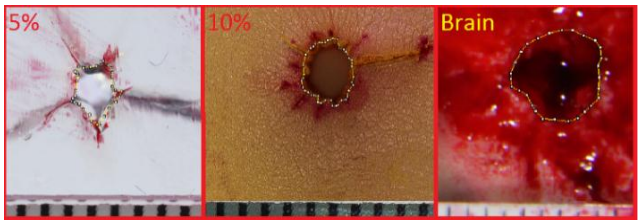

Figure 6. Measurement of the area of the wound track

All the measurements are the average of 2-3 repeated experiments for each material (some of the experiments failed as the impact was close to the boundary of the material). The error bars in Figure 7are ±2%, which occurs due to pixilation in image processing. The average area of the permanent wound track in bovine brain was 18 mm^2 and for 10 and 5% gelatine was 3 mm^2 and 3.7 mm^2 respectively. The average area of the permanent wound track in M1 was 54 mm^2.

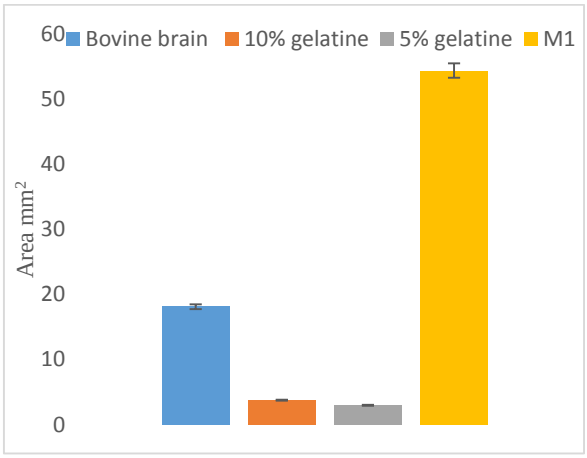

Figure 7. Average area of the polygon fit to the wound track

(Air Flow Visualisation)

Figure 8 shows sequence of frames from one of the 10% gelatine samples. The first frame shows the bullet before entering the smoke sheet. The second frame shows the moment the bullet exits the smoke. Frames 3 to 5 shows the smoke traverse laterally towards the bullet entry point and the evolution of the entry wound. From frames 6 to 10, the displacement of the smoke was measured by tracking the fastest contrast features through consecutive frames. The same procedure was applied to all the videos.

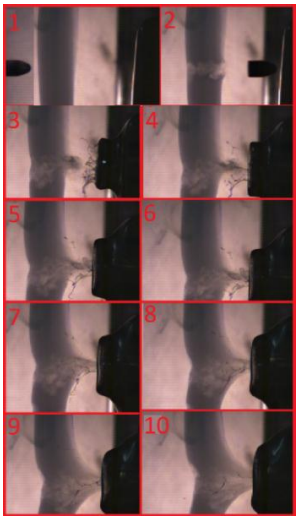

Figure 8. Example of the air motion into 10 % gelatine.

The relaxation time and Stokes number of the smoke particles were calculated to determine whether the smoke would follow the air as it moves. Dimensions of the particles were measured using a Dantec Flowsense 2Mpix PIV camera with 50 mm lens and 300mm extension tube. Particles were illuminated by a 15Hz dual head 120 mJ Nd:YAG laser (New Wave Solo XT). The calibration was performed using a fixed wire with a diameter of 0.4 mm, held in the focal plane and lit from behind. The wire was removed and the smoke particles were illuminated by the laser, another image of the particles were captured and knowing the dimensions of each pixel it was possible to calculate the dimension of the particles.
The Stokes number for a 1.6 micron particle of propylene glycol in this experiment for 100 m/s air flow is 0.009 assuming the streamline of curvature is 0.09 m (diameter of the bullet). The maximum velocity of the air observed in this experiment is actually 76 m/s. This shows the maximum error in velocity calculation will be less than 6% [12]. Figure 9 shows the velocity of the air as it enters and is ejected from the entrance hole in the gelatine samples.
The air was observed to move into the entrance hole at the moment of formation of the temporary cavity with an average velocity of 64.8 m/s, 75.6 m/s and 81 m/s fora10%, 5% and 3% gelatine sample respectively. The average velocity of the air ejected from the entry hole was 72 m/s for 10% gelatine, 43 for 5 % gelatine. However, measuring the velocity of the ejected air from 3% gelatine was not possible as the displacements of the particles were non-uniform and very slow. Error bars in Figure 9 shows± the difference between the average and the extreme values.

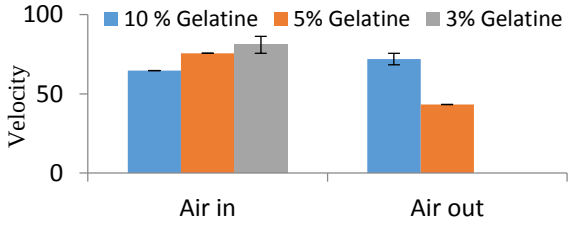

Figure 9. Velocity of the air into and out of the entrance wound in gelatine

Discussion

The stopping distance of the projectile in 10 % and 5% gelatine was 260 mm and 395 mm respectively. The stopping distance in brain was 390 mm showing that 5% gelatine produces the more physiologically realistic stopping distance. However, the area of the permanent wound cross sectional area in brain was 18 mm^2. For gelatine with 10 % and 5 % concentration, the average was 3 mm^2 (4 times less than brain) and 3.7 mm^2 respectively. For the M1 it was 54 mm^2, which is much higher than bovine brain. The

elastic response of the gelatine samples caused them to recoil to their original shape, and the form of the damage was not comparable with the bovine brain. A temporary cavity is known to form in gelatine when penetrated by 9 mm bullets [3, 4]. The temporary cavity has been hypothesised to explain the zone of stretched material surrounding the permanent wound track in muscle [2-4]. However, the size of the temporary cavity in brain may not match the size seen in gelatine due to a difference in material properties. It is possible to change the Young's modulus of the gelatine samples by reducing the percentage of the gelatine, which will change the elastic response of the material but the form of the damage shows that changing the percentage of gelatine alone is not enough to match the damage characteristics. Preliminary tests (not reported) show that by increasing the percentage of the corn starch in the M1 material it is possible to match the area of the permanent wound track to the bovine brain. This suggests a material with properties between M1 and 5% gelatine may be a better match to brain. The air motion observed from gelatine samples is the result of expansion and contraction of the cavity, which in turn depends on the elastic response of the material. As shown in Figure 9 there is a relation between the elastic response of the material and the velocity of the ejected air from the temporary cavity. Moreover, material with lower elasticity has a higher expansion rate. As shown in Figure 9, the air entering the cavity was observed to move inside with higher velocity as the percentage of gelatine decreased due to the increased expansion rate. The opposite response can be seen in the contraction of the material. The higher percentage of gelatine causes an increased rate of recoil as shown in Figure 9. The velocity of the ejected air therefore increases from 5-10% concentration. In the 3% gelatine samples, the ejection of the air was unquantifiable as the air motion was not uniform and of low velocity. Ejection of the air was not observed from the M1 samples. It must be noted that the M1 has the lowest elastic modulus compared to all the other materials used in this study. With low elastic modulus, the elastic response of the material may not be enough to move the air inside and outside the cavity. In the head samples, there was no observed air ejection. It is hypothesised that increasing viscosity may reduce permanent damage area while preserving the correct temporary cavity dynamics.

Conclusions

Visualisation of the air motion in front of the entry hole in the gelatine samples using a high-speed camera and smoke was investigated. Air motion was not observed from the animal heads, and it is hypothesised that the elastic response of the brain may be much lower than the gelatine. Shape and size of the samples can have significant effects on the pressure distribution and size of the temporary cavity [3]. The results of this experiment may help to develop a better finite element model of the ballistic impact to the head. In addition, it is suggested that a new material with more viscous properties must be used as a brain simulant for high velocity impact experiments. The form of the damage and elastic response in the 10 % gelatine is not comparable with the bovine brain. Neither M1 nor gelatine reproduced the same form and size of the permanent cavity. It must be noted that M1reproduces a more similar form of the tail splash and fragment dispersal compared to all the other simulants used in this study. Overall, this study suggested that for each specific problem a specific simulant must be prepared. One simulant might be suitable for the form of the damage and another one for the form of the fragmentation. The results suggest that 10% gelatine cannot be used as simulant for human brain.

Acknowledgements

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